# Revisiting $F_2$ laser for DUV microlithography

Thomas Hofmann, Jean-Marc Hueber, Palash Das, and Scott Scholler

Cymer Inc., San Diego, CA 92127

## ABSTRACT

A molecular fluorine laser, specifically tailored for photolithography needs, was developed. Single line operation at 157.6 nm was achieved by means of a prism assembly. Laser operation at repetition rates up to 2 kHz without signs of power saturation resulted in an average power of 20W. The energy stability was equal to comparable ArF lasers. Proper choice of materials and corona pre-ionization enabled gas lifetimes in line with current ArF laser technology, without any need for cryogenic purification.

**Keywords**: Fluorine laser, microlithography, high repetition rate

## INTRODUCTION

As the semiconductor industry is moving towards ever smaller feature sizes shorter wavelength light sources such as the molecular fluorine laser at 157 nm are needed. To date, most F2 lasers have been developed for materials processing or chemical and spectroscopic research. Little attention in development or even diagnostic has been paid to the main requirements on lithography lasers such as narrow linewidth, high energy stability and high repetition rate. In this work, a molecular fluorine laser was developed with particular emphasis to photolithography needs.

The specifications on a fluorine laser for photolithography are to a large extent governed by the lifetimes of optical components. At the short wavelength of the fluorine laser only a limited number of optical materials are available. These materials exhibit a severe deterioration in optical performance when exposed to high intensity, short wavelength light over extended periods. In the interest of long lifetime of the illumination optics it is therefore of utmost importance to reduce peak power generated by the fluorine laser. Reducing the peak power while maintaining a high average power level is possible by increasing the repetition rate or by lengthening the pulse duration. To date only sub-kilohertz repetition rates have been reported for the $F_2$ laser, but it is obvious that a viable lithography laser will require multi-kilohertz capability. Required power and energy levels will be similar to next generation KrF and ArF lasers on the 10-40W and 10mJ level.

The spectral linewidth requirement depends on the specific design of the illumination device. For a mostly reflective imaging design it will be sufficient to select a single line of the normally dual line broadband laser. A line selected $F_2$ laser will have a linewidth of a few picometers. If, however, a fully refractive imaging system will be used then the large dispersion of optical materials at 157nm will require a FWHM linewidth of about 0.2pm. Other beam properties such as energy stability, beam size, beam shape and divergence are expected to be similar to KrF and ArF lasers. Particular emphasis will be on cost of operation, which involves gas lifetime and module lifetimes, primarily the laser chamber and all optical components. A summary of specifications is given in table I.

The laser presented in this study is largely based on current production KrF and ArF lasers. This approach was chosen as the quickest and most cost effective way to develop a microlithography $F_2$ laser. Relying on proven technology ensures a low risk design and straight-forward implementation into production. Particular emphasis was placed on direct comparisons with current ArF lasers. Using ArF as a benchmark of well-characterized performance makes it easier to judge the $F_2$ laser achievements in terms of maturity for photolithography.

## EXPERIMENTAL RESULTS

The laser utilizes a recently developed high efficiency chamber with Brewster angled windows. Solid-state pulsed power excitation provides long lifetime and reliable laser operation. The discharge is corona pre-ionized to minimize gas contamination. The entire optical beam path is nitrogen purged to avoid light absorption by oxygen and to avoid damage to optical components. All resonator optics were placed external to the laser chamber. The gas mixture typically consisted of 0.05% - 0.1% fluorine in 4 atms of helium. The electrode gap was reduced to 10 mm to keep the discharge voltage on an easily manageable level. The laser power was measured by a standard power meter and cross-correlated with a piezoelectric Joulemeter. Contributions of the red, atomic fluorine laser were subtracted and usually amounted to less than 1% of the total

energy. By venting the beam delivery tubes to air, which strongly absorbs 157nm light, the red radiation could be measured.

The dependence of broadband laser power upon repetition rate is displayed in figure 1. The laser power increases almost linearly with repetition rate and approaches a power of 20W at 2 kHz. The laser power at 1950 Hz was solely limited by the charging power supply. Based on this linear relationship one can assume that the fluorine laser can be scaled to repetition rates beyond 2 kHz, provided the gas flow is scaled accordingly. Since we are using helium as a buffer gas only a fraction of the blower power of standard neon based lasers is required and therefore does not present a limitation to higher flow speeds.

A good measure for energy stability is gained by observing the energy transient in burst mode. For this the laser is repeatedly fired in bursts and the average energy for every pulse position in the burst is recorded. Also, for every pulse number in the burst the average variation in energy from burst to burst is calculated. The resulting energy and stability curves for the fluorine laser and for comparison also for a line-narrowed ArF laser are displayed in figure 2. The fluorine laser exhibits only minor energy variations over a 120 shot burst. The energy stability shows an initial increase in the beginning of the bursts and then stabilizes on a 3 sigma level of about 3%. By contrast the ArF laser exhibits a large transient in the energy and a 3 sigma instability around 7%. The ArF laser obtained a dose stability of 0.5% in a 60 pulse window, therefore the fluorine laser is expected to deliver at least the same dose stability.

The pulse durations of the fluorine laser and of an ArF laser are displayed in figure 3. While the 12ns FWHM pulse duration of the fluorine laser is somewhat shorter than that of the ArF laser it may still allow for limited line-narrowing.

A spectrum of the broadband fluorine laser as recorded by a VUV spectrometer is shown in figure 4. Clearly visible are the two transition lines at 157.52nm and at 157.63nm. 87% of the laser energy is located in the longer wavelength line at 157.63nm. The transition at 156.7 nm was not observed. Single-line mode operation at 157.63 nm was achieved by tuning with a set of two external prisms. The laser could also be tuned to the 157.52 nm transition line, but at reduced efficiency. Also shown in figure 4 is an expanded view of the laser line at 157.63nm. Convolved linewidths of 1.14 pm FWHM and 2.35 pm 95% were measured. These linewidths are much narrower than previously expected. Therefore, a line selected fluorine laser without additional line-narrowing will be sufficient for all but fully refractive imaging systems. The laser power vs. repetition rate behavior of the single line laser exhibits the same linear rise as the broadband laser. However, the maximum power in this initial experiment was limited to 4W. The reduced output power was caused by reflection losses in the line selection optics and by an overly long cavity length. A more efficient scheme is currently being implemented.

The horizontal and vertical beam profiles were measured at 1 m distance from the laser (Fig. 6). The beam shows smooth profiles with a high degree of symmetry. These kinds of profiles are easily managed by currently used homogenizer technology to produce very uniform illumination.

An estimation of the gas lifetime is derived by operating the fluorine laser at constant voltage without fluorine injection and recording the evolution of laser power versus the number of shots. No cryogenic purification was used in these measurements. As evident in figure 7 the laser power decreases by less than 20% after 4 million laser shots, which is at least as good as for comparable ArF lasers. From previous experience with ArF lasers one can thus estimate a gas lifetime of about 25 million shots by making use of periodic fluorine injections. This is clearly a result of the choice of compatible materials in the laser chamber and the use of corona pre-ionization. For KrF and ArF lasers a direct correlation between fluorine consumption and chamber lifetime was established, previously. We can therefore estimate a chamber lifetime of the fluorine laser on the same order as that of an ArF laser.

## CONCLUSIONS

We have successfully demonstrated the key parameters for a prototype lithography fluorine laser with only few straight-forward changes to current ArF laser technology. In particular the repetition rate, energy stability, beam profiles and gas life times are in line with current requirements on a fluorine laser for microlithography. The demonstrated linewidth is largely sufficient for predominantly reflection based illumination systems. For a refractive lens system it will be difficult to obtain ultra-narrow linewidth and high efficiency in a single system. We therefore propose an injection seeded master oscillator power-oscillator design. In this system a master oscillator, which is fully optimized for narrow linewidth at low energy, would seed a power oscillator, that is mostly optimized for energy extraction. In this way it would be possible to generated ultra-narrow linewidth radiation with high efficiency. Because the laser flux build-up time in the power oscillator is largely reduced by the injection seeding a longer pulse duration can be achieved. This will be especially important for optics lifetime. If a system can be designed with good synchronization between master oscillator and power oscillator, then also the energy stability can be improved. The reason for this is that the power oscillator is operating in the saturated regime for a longer time and therefore will be less sensitive to small gain variations.

## ACKNOWLEDGMENTS

We are grateful to Rick Sandstrom and Thomas Duffey for providing the linewidth measurements with their high-resolution spectrometer.

## $F_2$ Laser Requirements For Microlithography

| | | |
|---|---|---|
| • **Repetition Rate** | 1000 to 4000 Hz | Concerns About Optical Damage May Require High rep-rate, Low energy configurations |
| • **Energy** | 10 to 15 mJ | |
| • **Power** | 10 to 40 Watts | |
| • **Spectral Requirement** | | Accurate Spectral Properties of $F_2$ laser must be measured. Concern about impact of 0.2pm on CoO |
| - Wavelength | 157.56nm | |
| - Spectral Width | Single Line ~ 6pm or $\Delta\lambda_{FWHM}$ ~0.2pm | |
| • **Beam Properties** | | These properties are expected to be similar to KrF and ArF lasers |
| - Energy Stability | | |
| - Beam Size and Shape | | |
| - Divergence and Coherence | | |
| - Pulse width | | |
| • **CoO** | | Major Concern Today! |
| - Gas Life | | |
| - Module Life times | | |

Table I

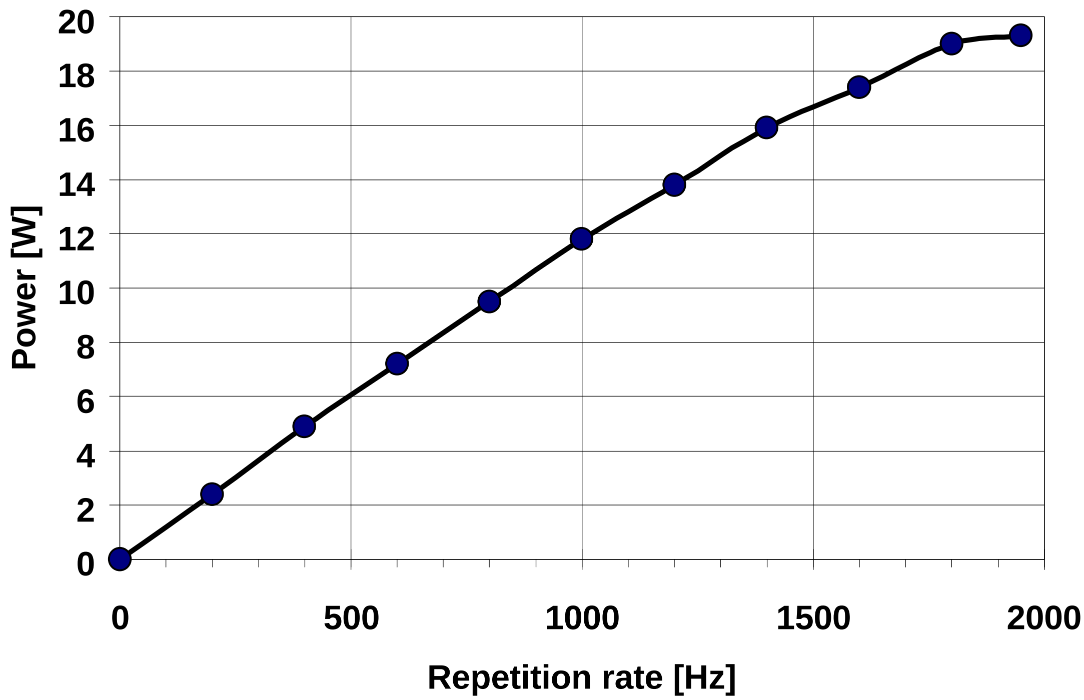


Figure 1  Dependence of broadband fluorine laser power upon repetition rate

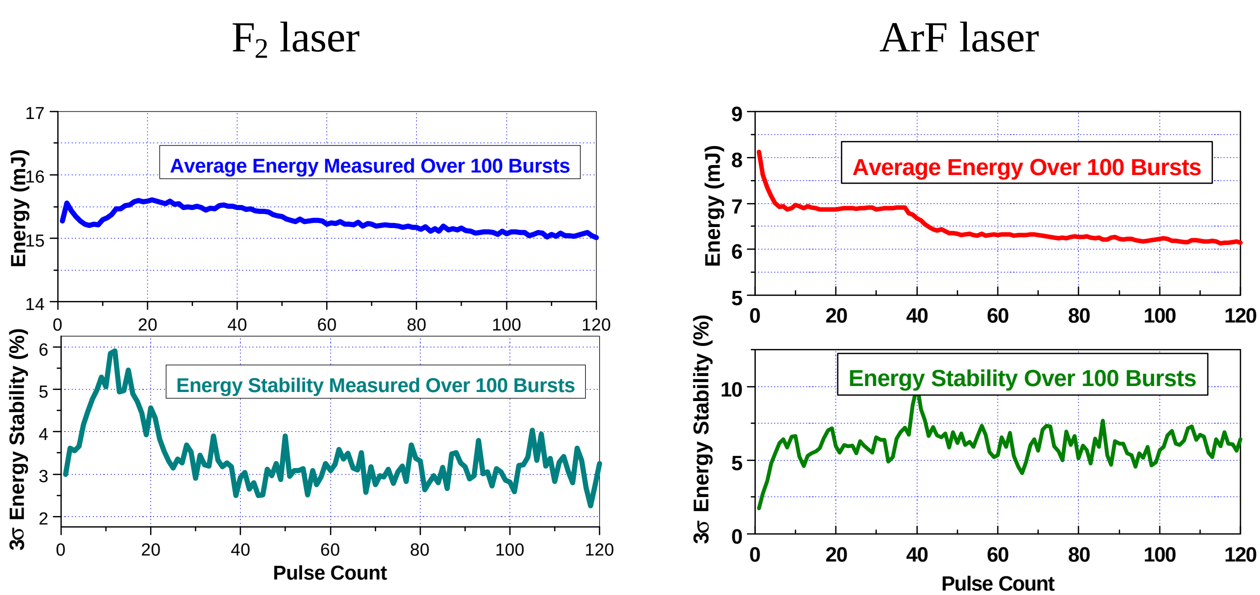


Figure 2   Average energy and energy stability burst transients of $F_2$ and of ArF lasers

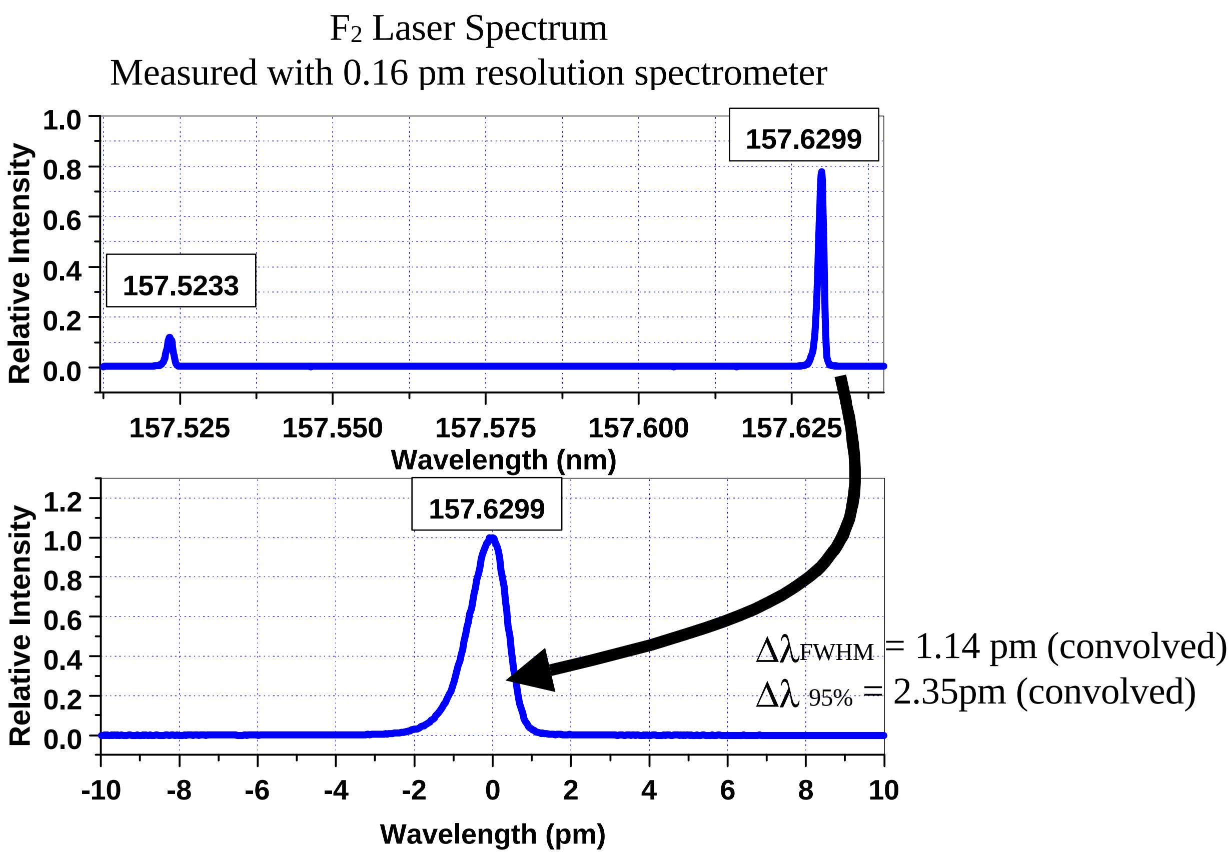


Figure 4 Spectra of the broadband and single line fluorine lasers

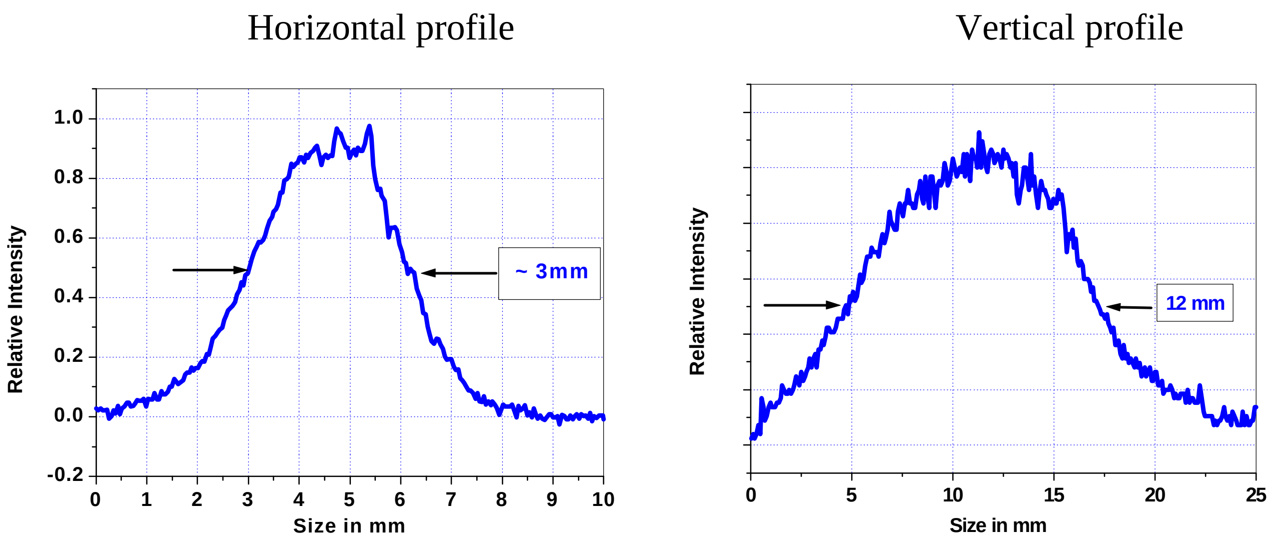


Figure 5 Horizontal and vertical beam profiles at 1 m distance from the laser

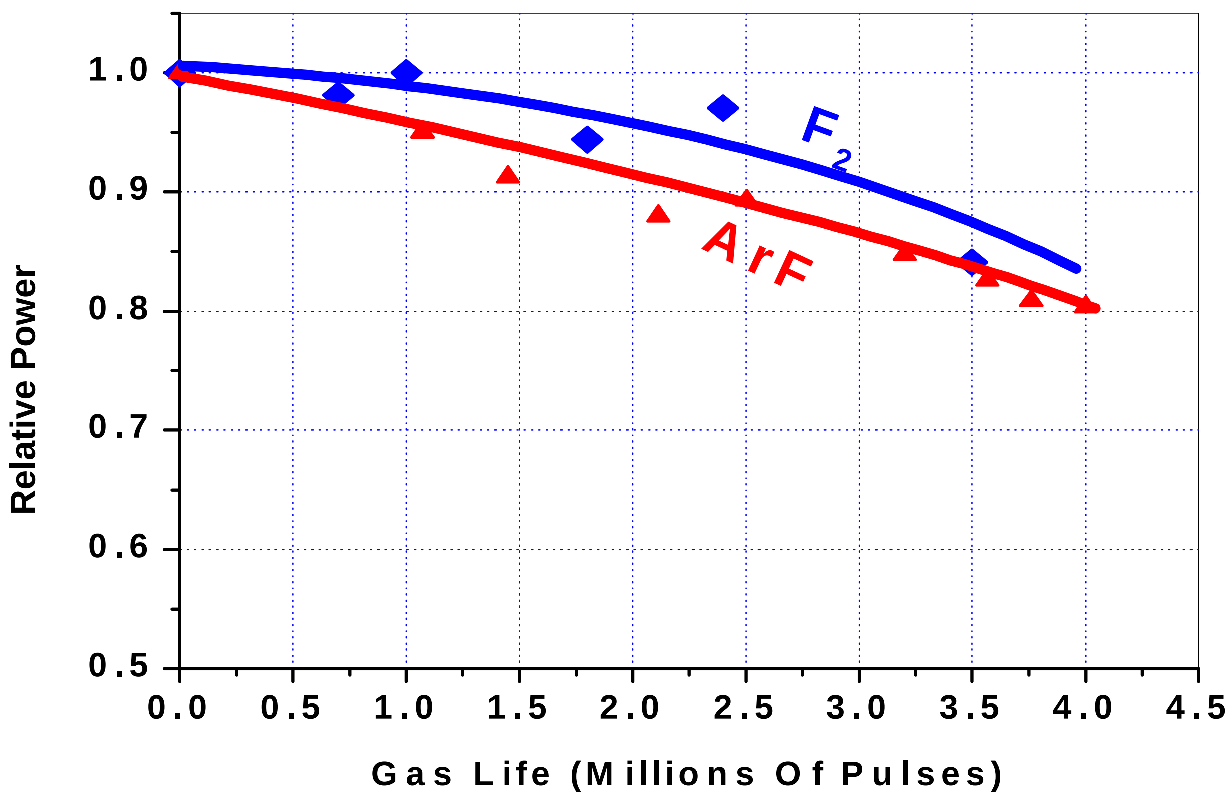


Figure 6 Dependence of laser upon number of laser shots at constant charging voltage